THERMAL RECOVERY OF OIL FROM TAR SANDS BY AN ENERGY-EFFICIENT PROCESS

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Oil-impregnated rock deposits, more commonly referred to as tar sands, are found on every continent except Australia and Antarctica [1]. The largest known deposits occur in northern Alberta, Canada, where two full-scale commercial plants for producing synthetic crude oil are in operation and two more plants have been approved for construction. Of the 24 states that contain tar sands in the United States, Ritzma [2] estimates that about 90-95 percent of these tar sands lie in Utah. Although the Utah deposits contain only about 25 billion barrels of in-place bitumen, compared to 900 billion barrels in Canada, as discussed by Oblad et al. [3], the Utah deposits represent an important potential domestic source of synthetic petroleum.

Operating plants in Canada employ a hot-water process for recovering bitumen from tar sands. Although Utah tar sands can be considerably different from Canadian tar sands with respect to physical and chemical properties [4], Sepulveda and Miller [5] have successfully processed tar sands from high-grade Utah deposits with a modified hot-water process that uses high-shear conditions to overcome the higher viscosity of Utah tar-sand bitumens. More recent work by Misra and Miller [6] has been successful in processing medium-grade Utah deposits. Other methods for processing tar sands that have been studied extensively [1] include various in-situ techniques and mining followed by direct coking, solvent extraction, or cold-water separation. Of the other methods that use mined material as the feed stock, direct coking processes, generally referred to as thermal recovery methods, appear to exhibit the most promise as alternatives to hot-water processing because thermal recovery methods avoid handling of viscous bitumen, recovery of sediment from solutions, and recovery and recycle of water and/or solvents. In the work presented here, a new energy-efficient thermal process was developed and applied to tar sands from three Utah deposits.

THERMAL RECOVERY PROCESSES

The concept of recovering liquid and/or gaseous hydrocarbons from solid hydrocarbon-bearing materials by thermal treatment has been known for several centuries [7]. Thermal treatment essentially entails processing at high temperature. In most thermal processes, the feed material is heated in an inert or non-oxidizing atmosphere. The mode of heating and the operating temperature largely determine the type of changes occurring to the feed, which can include: 1) volatilization of any low-molecular-weight components in the feed, 2) generation of vapors by cracking reactions, and 3) conversion of part of the material into coke, by reactions such as polymerization. In the case of feed materials such as tar sand, which contain a significant amount of silica sand or other inorganic inert matter that remains substantially unchanged through the thermal treatment, coke is obtained as a deposit on the inorganic matter.

Thermal processing can require a substantial input of energy to provide the necessary sensible, latent, and reaction heats. However, as discussed by Oblad et al. [3], coke, when produced as above and subsequently combusted, can generally provide much or all of this energy requirement. Combustion, referred to by some authors as decoking or burning, is therefore an important aspect of thermal-recovery methods.

Moore et al. [8] classify thermal processes into two general groups, direct heated and indirect heated, depending on whether pyrolysis and combustion steps are carried out in one or two reaction vessels. The processes further differ from each other with respect to fluidized-bed or moving-bed state of solids in each of the two steps. Table I shows a general process classification scheme that fits most known thermal processes. References are included in that table. Regardless of the thermal process used, as discussed in detail by Bunger [4], the synthetic crude oil product obtained cannot, in general, be used as a substitute for crude petroleum but must be upgraded to reduce sulfur and nitrogen contents, average molecular weight, and C/H ratio.

In all thermal recovery processes, tar sand is subjected to high processing temperatures, about 450-550°C for pyrolysis, and the residual coked sand is further heated to about 550-600°C during the combustion step. At these conditions, an acceptable thermal efficiency can only be obtained if a significant portion of the sensible heat in the spent sand is recovered and introduced back into the process. Almost all the processes in Table I provide for heat recovery from spent sand before it is discarded.

Perhaps the best known fluidized-bed process is the one developed by Gishler and Peterson [17, 24, 25] in Canada. The process scheme resembles that of catalytic cracking as used in the petroleum industry. Tar sand is fed to the pyrolysis or coker bed, where the oil vapor produced is carried by the fluidizing gas to the product collection system. Coked sand is withdrawn from the coker and blown by preheated air into the burner where the coke is burned. A portion of the hot sand is recycled to the coker to supply heat for the pyrolysis step, with the remainder discarded through an overflow pipe in the burner bed. Two serious drawbacks of this process, as noted by Camp [1], are the large recycle of hot sand required and the high energy content of the net spent sand. Rammler [23] has described the application of the Lurgi-Ruhrgas process to tar sands. Like the Gishler and Peterson process, it uses sand as the heat carrier.

DEVELOPMENT OF AN ENERGY-EFFICIENT THERMAL PROCESS

The particulate nature of the mineral matter in most tar sands permits fluidized processing with several advantages: 1) disintegration of lumps of tar sand to individual particles upon the pyrolysis of the bitumen; hence such feeds do not have to be reduced to a small size prior to entry into the pyrolysis reactor; 2) relative ease of handling solids because fluidized solids flow through pipes like liquid; 3) high heat-transfer rates between fluidizing medium and solid particles; 4) nearly isothermal operation, which permits close control of the temperature of pyrolysis, a variable affecting product yields, quality, and energy requirements; 5) high rates for mass transfer between particle surface and fluidizing medium, which is important for a high rate of feed per unit area without forming agglomerates; 6) accommodation of variations in bitumen content of feed by regulating the flow of fluidizing gas; and 7) ease of immersion of heat transfer tubes or heat exchangers in the fluidized beds with accompanying high heat-transfer coefficients. The last factor is particularly important for the type of process developed in this study and constitutes the primary reason for the choice here of fluidized pyrolysis. A fluidized bed recommends itself for burning coke for essentially the same reasons as for pyrolysis and was used, therefore, for the process developed here.

Previously developed processes employ various features to accomplish heat transfer for preheat and pyrolysis. These include 1) preheating the tar-sand feed, separately from the pyrolysis step, generally to recover heat from outgoing hot gaseous streams; 2) preheating the incoming process gas streams, generally to recover heat from spent sand or solids residue leaving the process; 3) transfer of heat from the burner to the pyrolysis reactor in the form of sensible heat of gases leaving the burner, generally by direct heat exchange with the contents of the pyrolysis zone; and 4) internal combustion of coke in the pyrolysis reactor itself with a controlled amount of oxidizing gas so that only a portion of the hydrocarbons in the pyrolysis zone, preferably coke, is combusted; 5) transfer of heat from the burner to the pyrolysis step by recycle of hot, spent sand as a heat carrier.

Feature 1 has not been shown to be practical because, when preheated, tar sand becomes soft and sticky, making it impossible to feed by common feeding devices such as a screw conveyor. Feature 2 can be and generally is incorporated into most thermal processes. However, a maximum of only about 25 percent of the energy in the hot, spent sand can be recovered by preheating the oxidizing gas for coke combustion. In Feature 3, the amount of energy that can be carried by gases from the combustion zone to the pyrolysis zone is relatively small. Feature 4 requires a means for direct heat transfer between the two zones by conduction, convection, and/or radiation. Unless this can be accomplished on a large scale with little or no combustion of bitumen, Feature 4 is not practical. Feature 5 is practical, but excessive recycle of hot, spent sand is required, thus greatly increasing the required sizes of pyrolysis and combustion reactors and necessitating large devices to convey the sand.

Another possible means of transferring heat from the coke-combustion stage to the pyrolysis stage is by the use of indirect heat exchange not involving sand or gas. In the process developed in this work, this means was implemented by incorporating heat pipes to transfer the bulk of the energy required for solid preheat and pyrolysis from the coke-combustion stage. A heat pipe, for the purpose here, may be defined simply as a completely enclosed tubular device with very high effective thermal conductance, which transfers heat by two-phase circulation of a working fluid [28].

In operation, heat is transferred to one end of the heat pipe, causing the working fluid to vaporize. The vapor flows to the other, cooler end due to the pressure gradient set up inside the central vapor core of the heat pipe. There, the vapor condenses on the tube wall and inside a wick, transferring heat to the surroundings. The condensate then returns to the warmer end, thus completing the cyclic flow of the fluid. Because a large amount of heat can be transferred by a heat pipe, its so-called effective thermal conductivity can be extremely high. For application to thermal processing of tar sands, potassium was selected as the working fluid.

The essential features of the reactor system for the new thermal process developed in the work reported here are illustrated in the simplified process scheme of Figure 1. Freshly mined and sized tar sand is dropped into the upper bed of a multi-staged fluidized-bed column. The upper bed is a pyrolysis reactor, which is maintained at a temperature of generally between 400 and 550°C. Here, bitumen in the feed is cracked and/or volatilized, leaving a coke deposit on the sand particles. The oil vapors and light hydrocarbon gases produced are carried off by the inert fluidizing gas to fines-separation and product-recovery sections, while coked sand flows down by gravity through a control valve to the burner section of the column where the coke is burned to generate heat. The burner is maintained at a temperature of generally between 550 and 650°C. Preheated air is used to fluidize the solids in the combustion bed and to provide oxygen for combustion. Gaseous products of combustion, mostly nitrogen and carbon dioxide, then flow upwards to fluidize solids in the upper bed as noted above.

A number of heat pipes, as required by the heat-transfer load, are placed vertically in the fluidized-bed column such that they extend into the pyrolysis and combustion beds as depicted in Figure 1. The heat pipes transfer excess heat generated in the burner to the pyrolysis reactor, thus maintaining the reactor and burner at proper temperatures.

Hot, spent sand leaving the burner flows down through a control valve to a heat-recovery section, where process air recovers heat from the spent sand. Additional energy can be recovered from the sand by heat exchange to produce steam. A more detailed description of the process is given by Seader and Jayakar [26].

The new process retains most of the simplicity of direct-heated processes. Solids move only downwards by gravity, the equipment is essentially a single vessel, and there is no recycle of solids. Most importantly, the heat-transfer features used--heat pipes, heat recovery from spent sand to preheat process air, transfer of some heat by combustion gases, and some radiative heat transfer from coke-combustion stage to the pyrolysis reactor--permit efficient management of the energy that is within tar sand itself to help achieve high energy efficiency. The heat pipes effectively link the pyrolysis reactor and the coke-combustion stage thermally without necessarily imposing any other constraints on the process such as flow patterns, reactor configuration, or dimensions of the column (except for the volume of heat pipes, which is a small fraction of bed volumes).

The basic process as outlined above is very flexible, and modifications and variations can be easily incorporated into it to further improve the overall efficiency and/or to make it more suitable for specific types of feeds. Thus, external fuel, recycle gas, or liquid fuels can be easily introduced into the burner in the case of lean tar sands. By providing for a purge gas stream off the top of the combustion bed, one can adjust the flow rate of fluidizing gas to the pyrolysis bed. If desired, after recovery, gas produced in the pyrolysis bed can be recycled back to that bed and used instead of combustion gases to fluidize it. This is very important for lean tar sands which would otherwise have very low product concentration in the combined exit gas stream, making product recovery difficult.

LABORATORY TESTING OF NEW PROCESS

A laboratory apparatus was used to demonstrate the new thermal process. It consisted of a 10-foot-high by nominal 2-inch diameter, two-staged, fluidized-bed column, a screw feeder for feeding tar sand, a hot cyclone and filter system for separation of fines from the products, and a product-recovery section consisting of condensers, phase separators, cyclones, and an electrostatic precipitator. A single 0.75-inch-diameter by 7-foot-long heat pipe extended into the pyrolysis and coke-combustion beds. The apparatus was completely insulated and instrumented with thermocouples, pressure taps, flow meters, and sampling taps. Electrical heaters and a propane burner were used to provide heat during startup conditions. The equipment was designed to handle a nominal feed rate of 5 lb/hr of tar sands containing up to 14 weight percent bitumen. Further details of the apparatus are given by Jayakar [27].

Several problems in solids handling were encountered in operating the laboratory apparatus. Originally solids were transferred from the pyrolysis bed to the combustion bed by means of a weir and dip leg. Because gas tended to flow up through the dip leg, this system was abandoned in favor of a simple solids downcomer with a specially designed solids flow-control valve. Although this valve permitted proper operation of the bed, it was a recurrent source of operating difficulty as it tended to stick after a few runs and had to be dismantled and cleaned every two to four runs. Flow of solids from the combustion bed was controlled by a similar valve, which presented no operating problems.

Tar-sand feed materials were ground to particles or pieces no larger than about 1/4-inch in size. Materials tending to be sticky were dusted with fines or coal dust prior to feeding. The screw feeder did not plug as long as it was kept at a near-ambient temperature. Run durations were typically one hour after spending several hours to reach essentially steady-state conditions.

The experimental work was divided into three parts: fluidization studies at elevated temperatures, processing of tar sands in the pyrolysis section without use of the heat pipe, and operation of the complete heat-piped apparatus. Only typical results of some of the latter tests are reported here.

A total of 75 runs was made under thermal processing conditions at near-ambient pressure with tar sands from three different deposits: Tar Sand Triangle, Sunnyside, and Asphalt Ridge. Data from representative runs for feed materials from each of the three deposits are given in Table II. A complete accounting of all the bitumen in the feed material was generally not achieved mainly because of difficulties in removing oil product from the product recovery equipment. Thus, values reported for oil yield are believed to be low. Based on the best runs, it is estimated that for Sunnyside and Asphalt Ridge materials, a typical yield structure for near-optimal operating conditions would be: 70 wt% oil, 10 wt% gas, and 20 wt% coke.

CONCLUSIONS

1. The basic concept of a thermal process using pyrolysis and combustion stages coupled by heat pipes is workable and eliminates the need to recycle large amounts of sand.
2. Tar sands containing as low as 8 percent bitumen can be thermally processed without external energy input to get satisfactory yields of oil. Tar sand with even lower bitumen content can be processed with good oil yield if a portion of the gas or oil products or some cheaper external fuel, such as coal, can be added to the combustion stage to provide energy.
3. Modifications of the process, such as introducing recycle of gas and oil, allowing for purge of some combustion gas, etc., can improve the energy efficiency of the process and the yields of oil and gas.
4. The process developed during the course of this work is simple, direct, and efficient. It is capable of wide application to processing of tar sands in Utah, Canada, and perhaps other deposits. Moreover, the concept of using heat pipes is of even broader applicability in the process industries in general and in energy-related industries in particular. For example, the basic processing concepts investigated here may have potential for application in the processing of oil shale and coal.

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TABLE I. CLASSIFICATION OF AND REFERENCES FOR THERMAL RECOVERY PROCESSES

	Direct Heated	Indirect Heated
Moving-bed pyrolysis and combustion	Cheney et al. [9] Dannanberg and Matzick [10] Saunders [11]	Bennett [12] Berg [13] Fitch [14]
Fluidized-bed pyrolysis and combustion	Gifford [15] Peck et al. [16]	Gishler and Peterson [17] Nathan et al. [18] Roetheli [19] Murphree [20] Alleman [21]
Fluidized-bed pyrolysis and moving-bed combustion	Donnelly et al. [22]	No examples known
Moving-bed pyrolysis and fluidized-bed combustion	No examples known	Rammler [23]

TABLE II. LABORATORY RESULTS FOR PROCESSING OF UTAH TAR SANDS

	Deposit		
	Tar Sand Triangle	Asphalt Ridge	Sunnyside
Run No.	58	67	74
Bitumen Content of Feed, wt%	4.70	11.67	10.56
Tar-Sand Feed Rate, lb/hr	3.85	3.90	4.41
Pyrolysis Bed Temperature, °C	475	482	449
Combustion Bed Temperature, °C	603	649	604
Oil Yield, wt%	49.5	52.7	45.4
Gas Yield, wt%	20.6	15.7	6.2
Coke Yield, wt%	22.0	7.8	17.2
Total Yield, wt%	92.1	76.2	68.8
API Gravity of Oil, 20°C	13.1	15.2	18.2
Viscosity of Oil, cps, 25°C	142	102	291

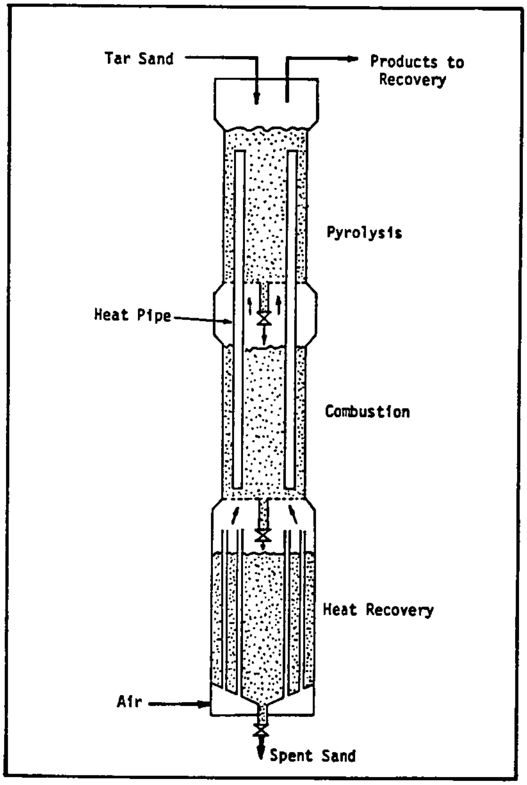

Figure 1. University of Utah Process